Geophysical Tests for Habitability in Europa and Other Ocean Worlds

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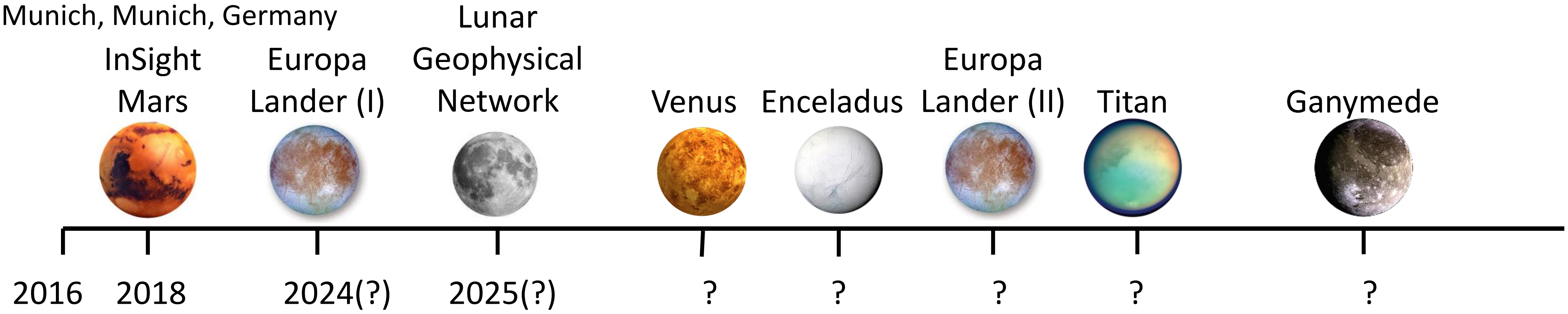
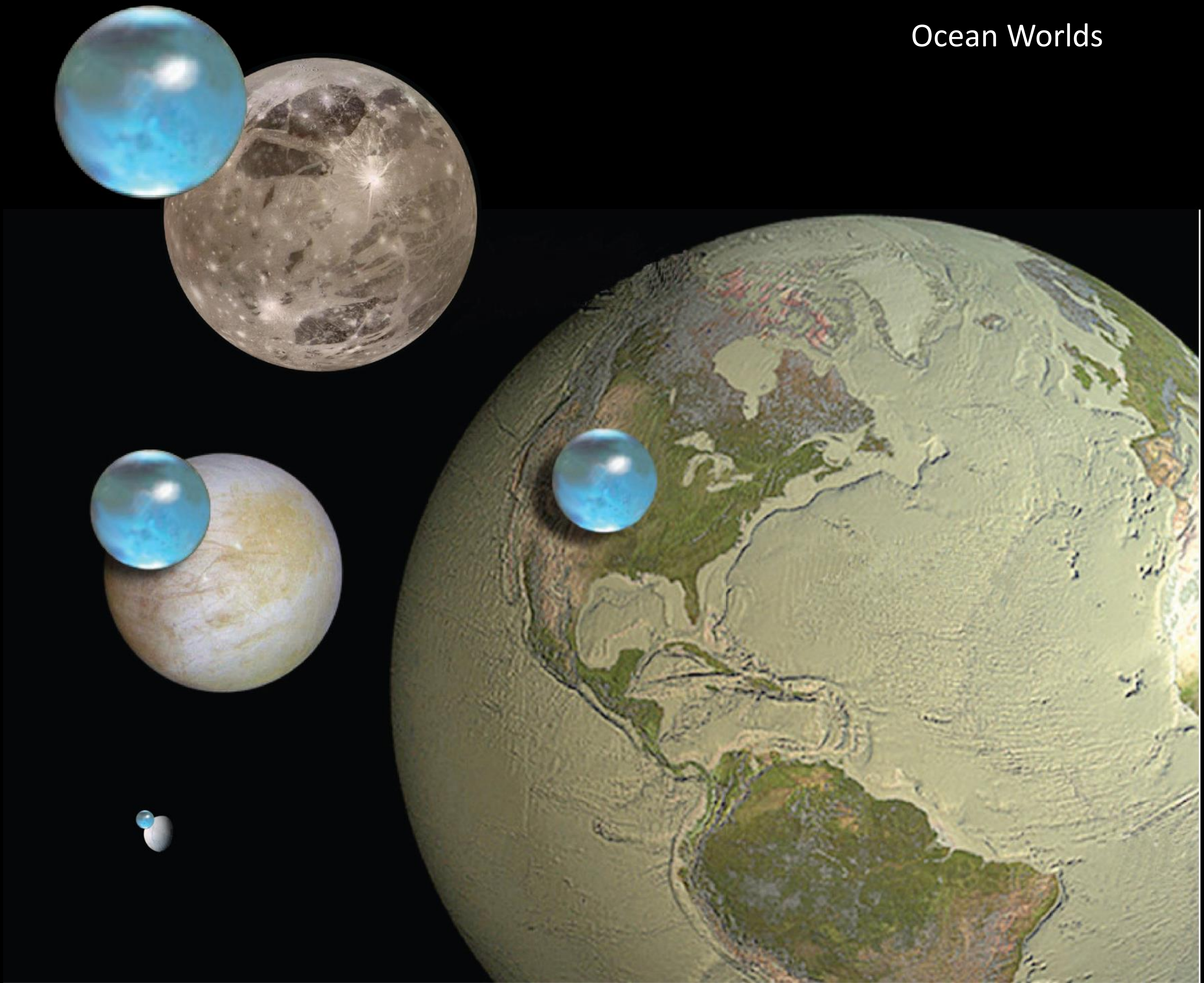


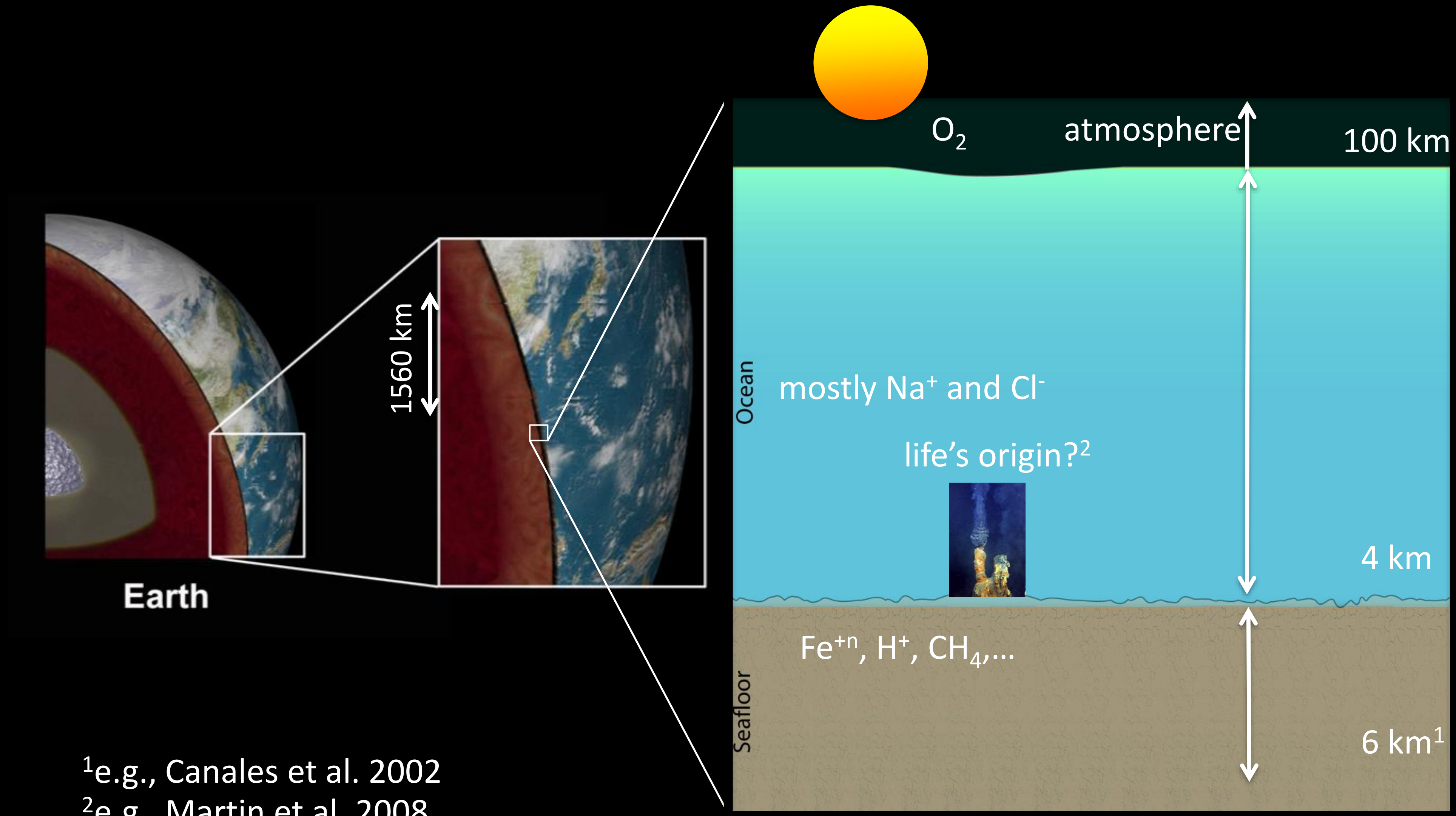
Seismology in Ocean Worlds

- How might ocean worlds be habitable?
  - Need to understand redox fluxes and reservoirs
- How might we use geophysics to test for habitability?
  - Focus here is on seismology

Ocean Worlds



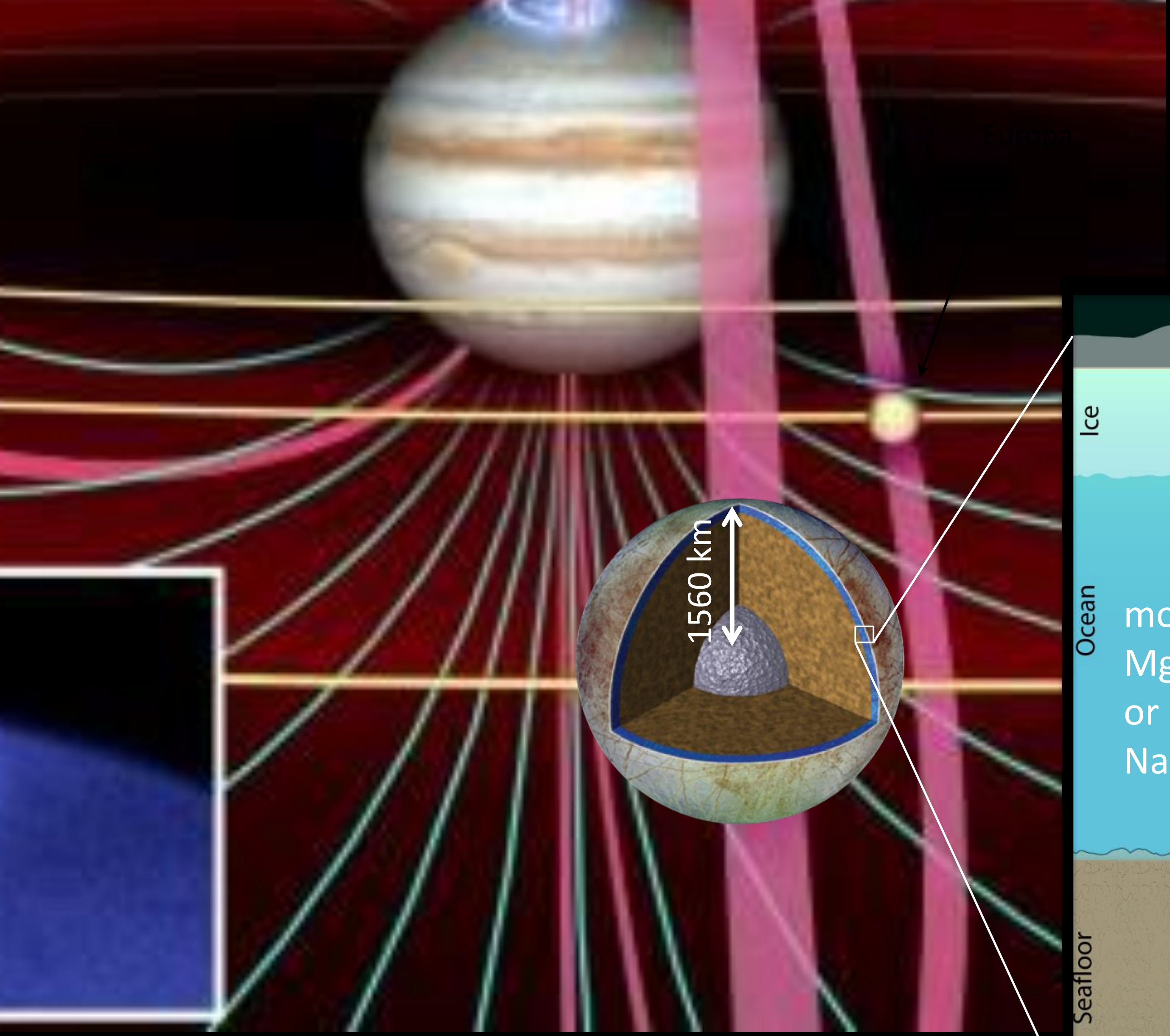
The Earth System

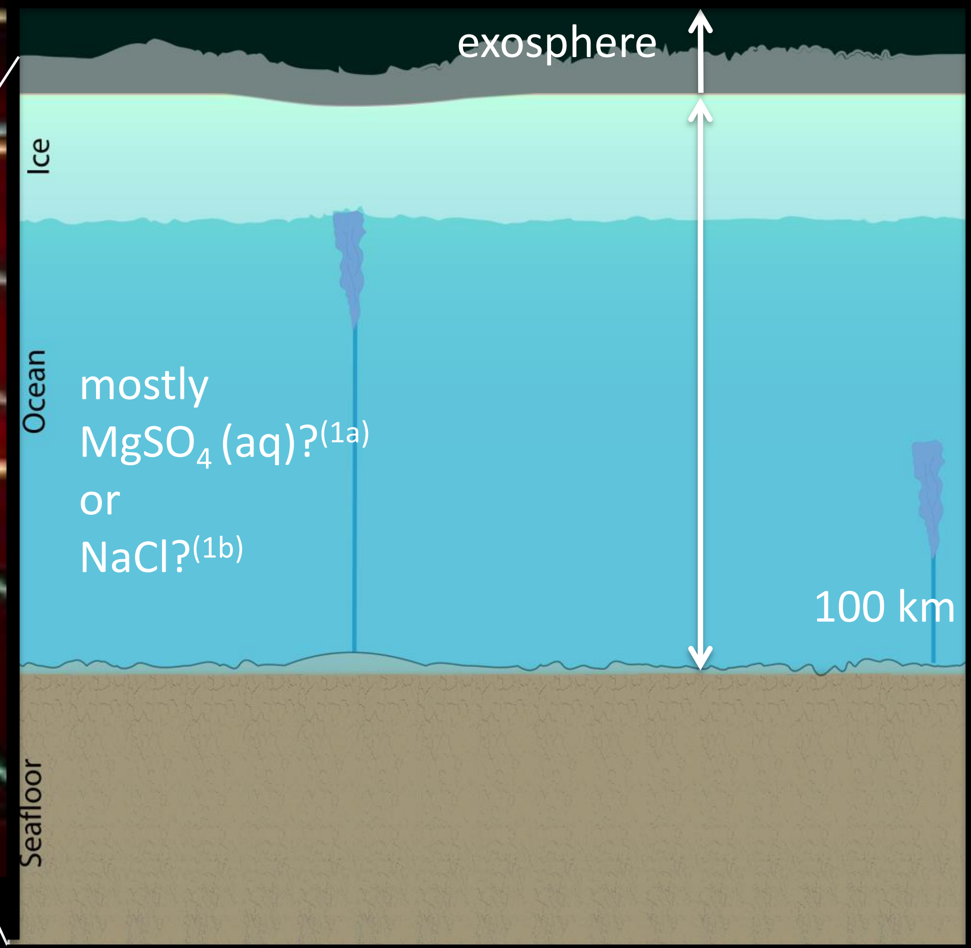


[1]e.g., Canales et al. 2002
[2]e.g., Martin et al. 2008

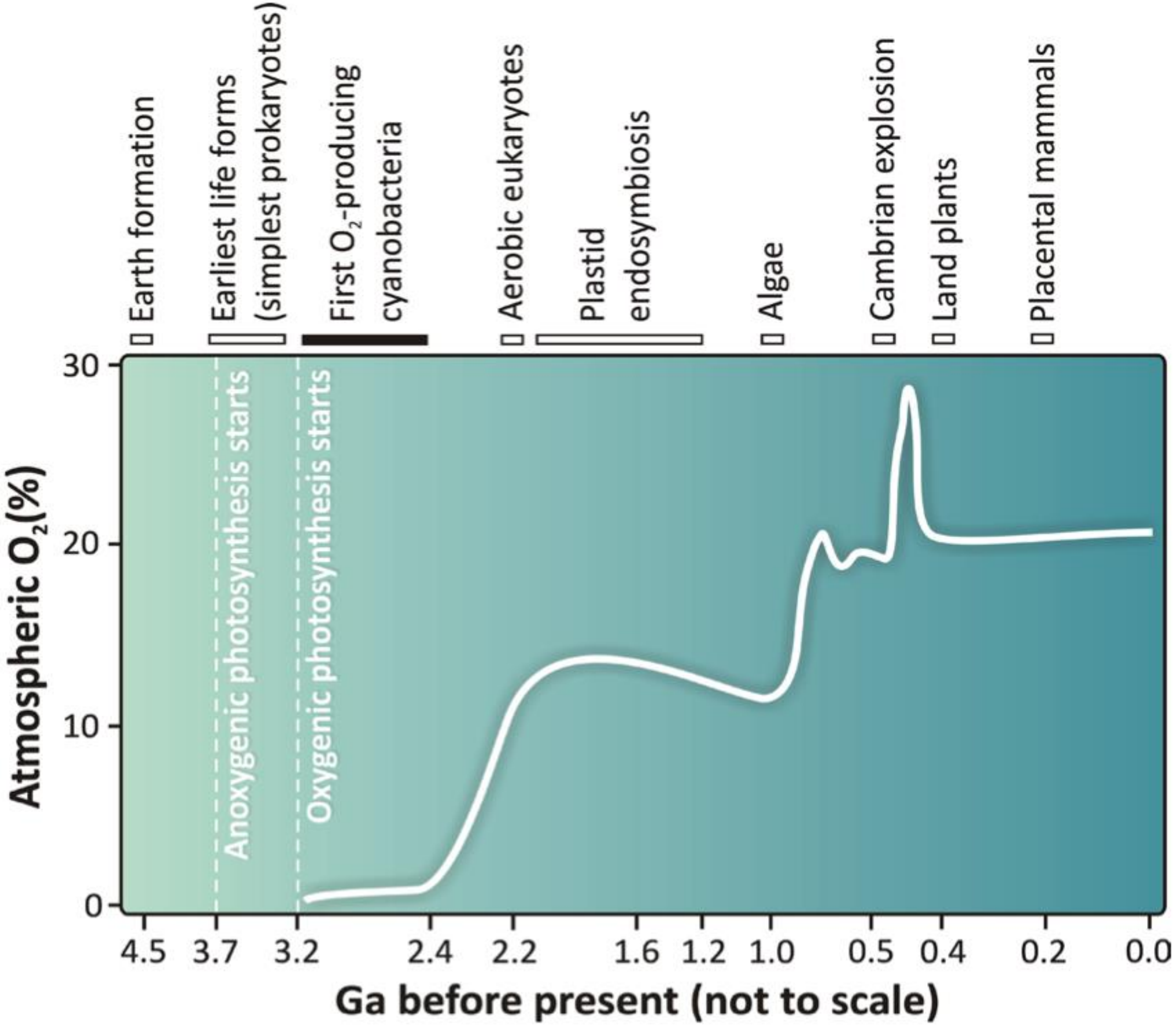
Earth Images: NASA

Europa



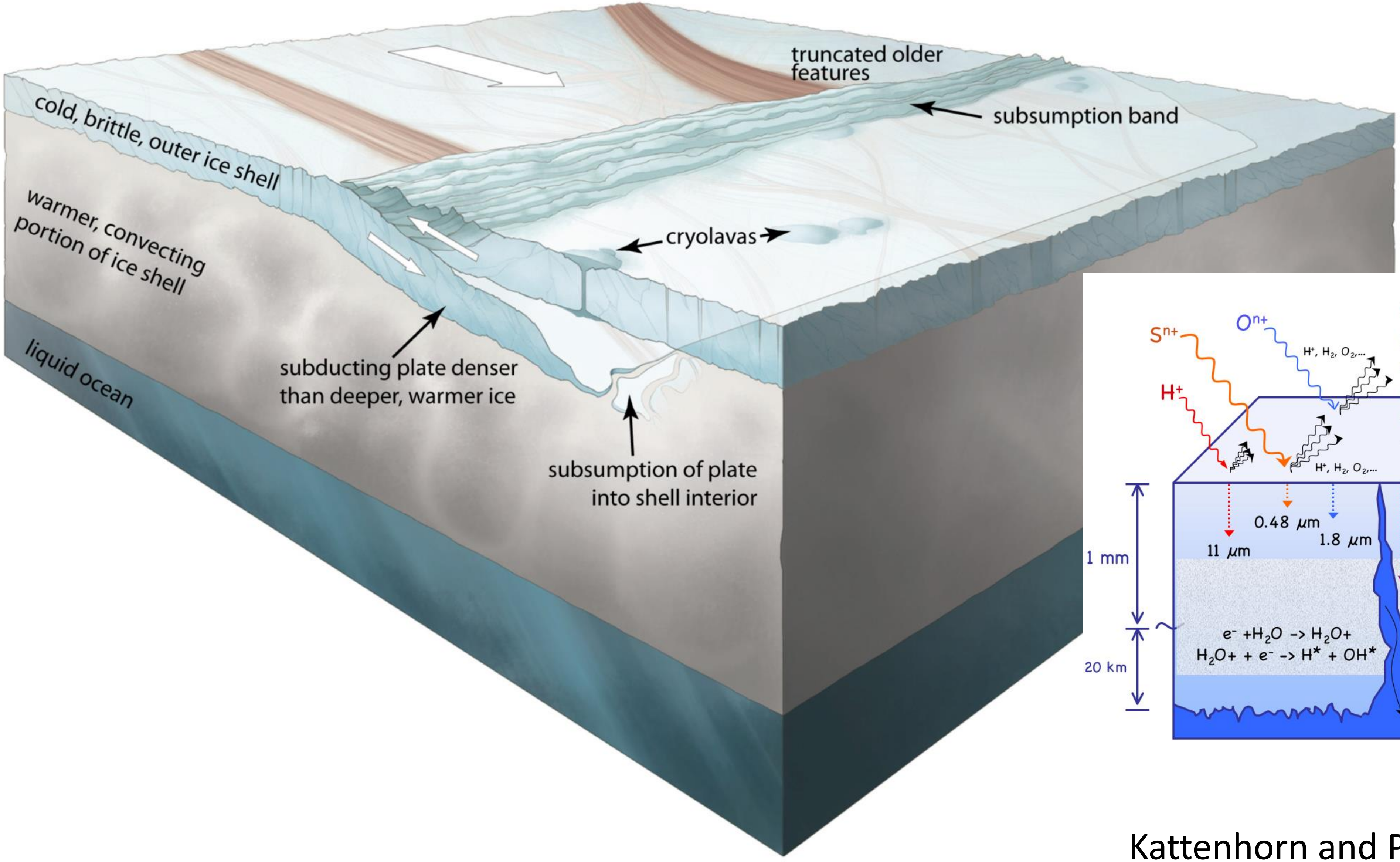


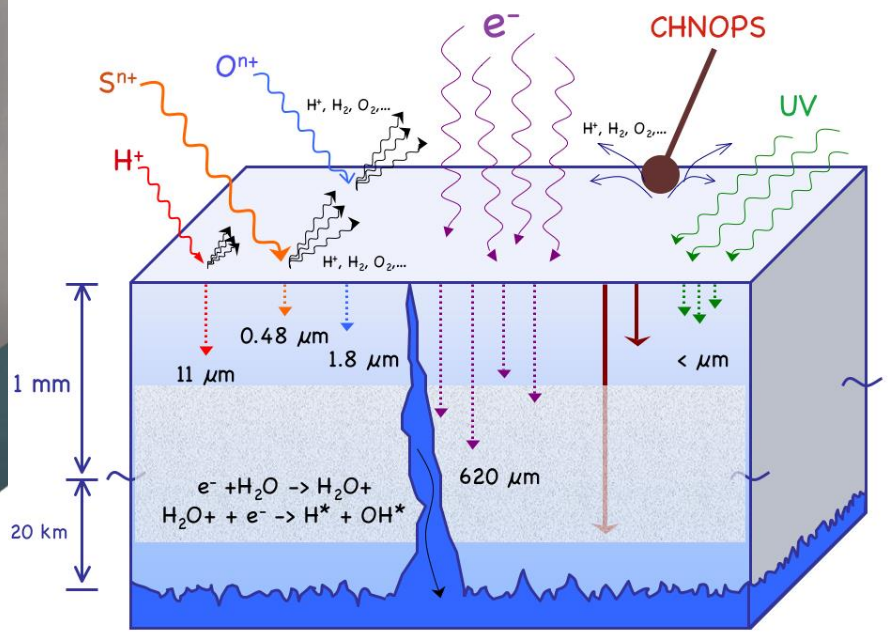
[1a]e.g., Zolotov and Kargel 2009
[1b] Brown and Hand 2013



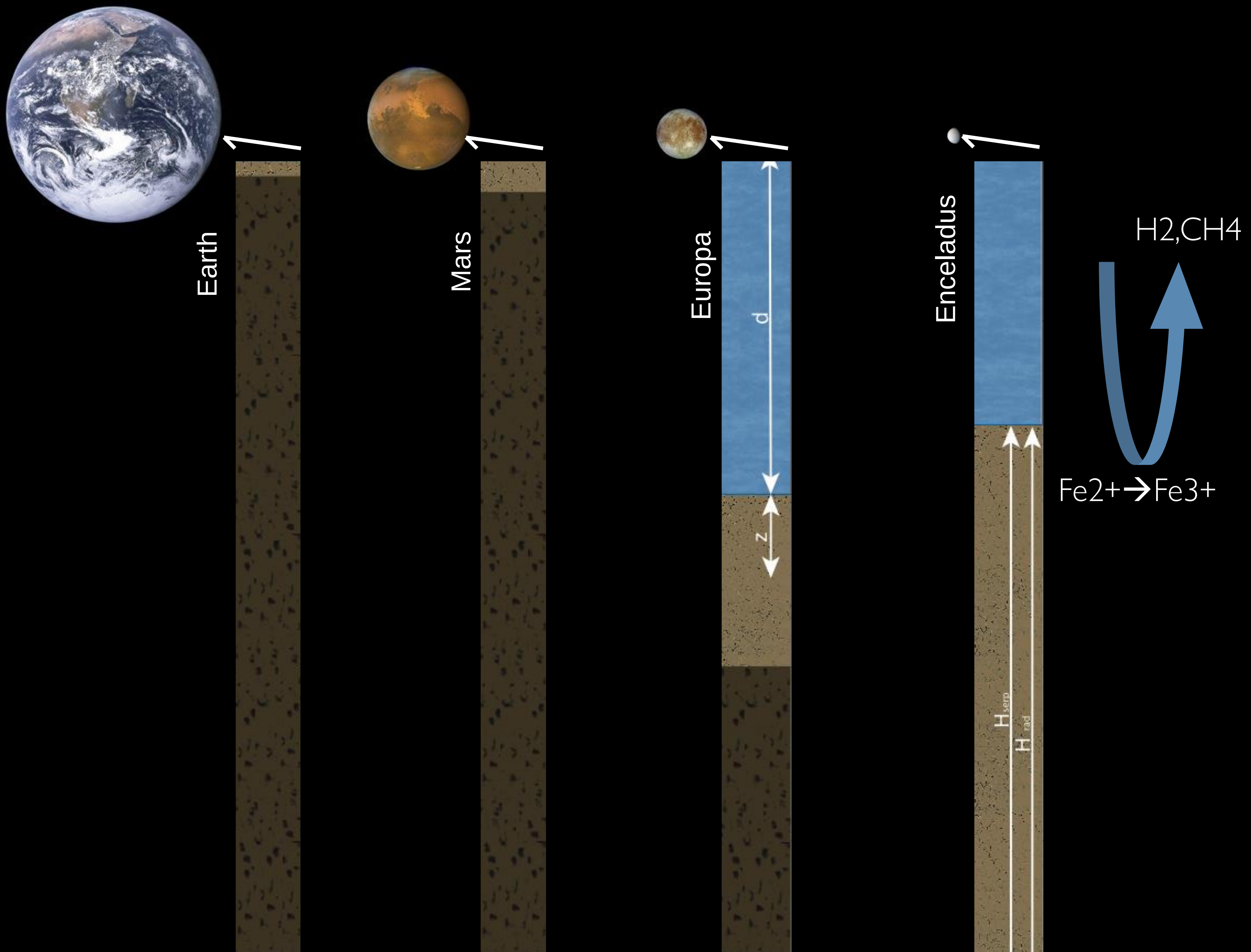
From "Adventures with cyanobacteria: a personal perspective," Govindjee et al. 2011

"Plate Tectonics" on Europa





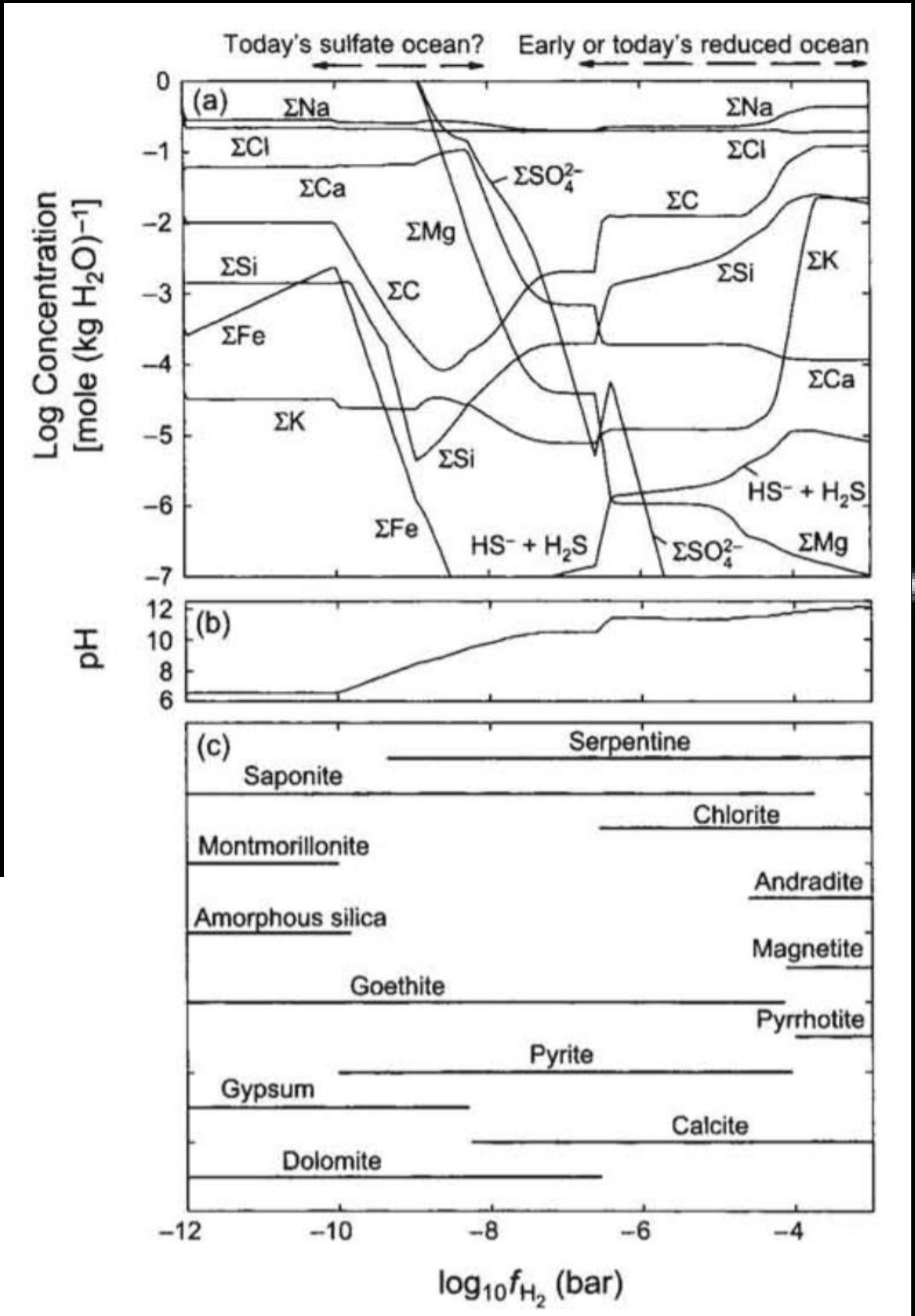
Kattenhorn and Prockter 2014



Earth
Mars
Europa
Enceladus
d
z
H2,CH4
Fe2+→Fe3+
H serp
H rad

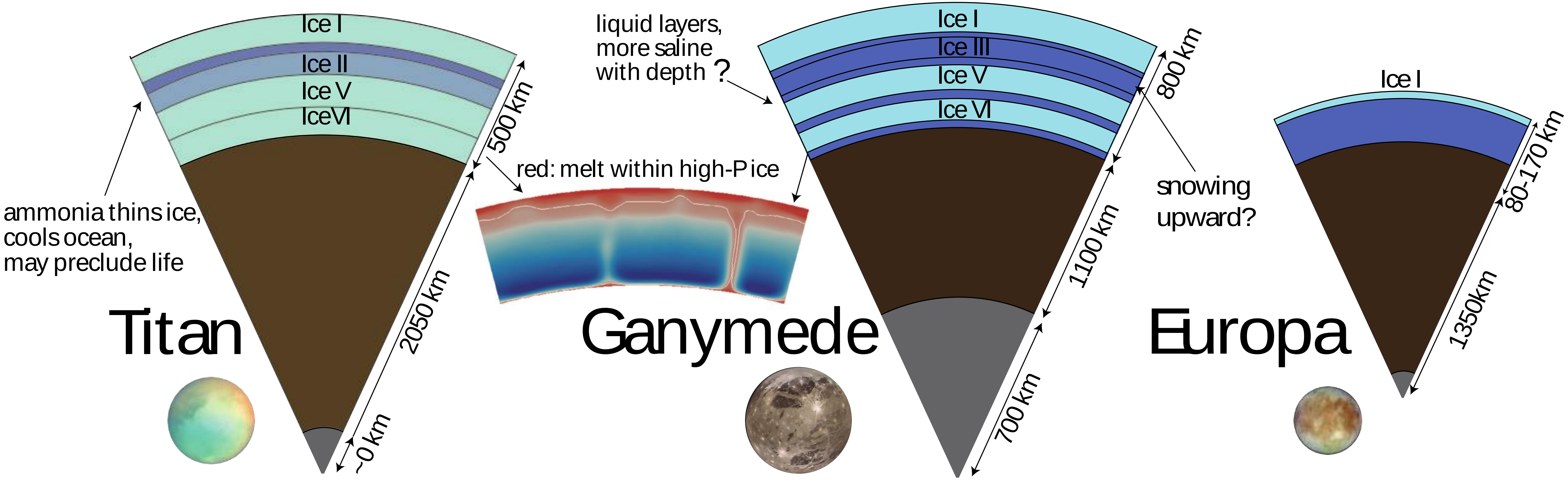
$MgSO_4$

?



NaCl

Zolotov and Kargel 2009

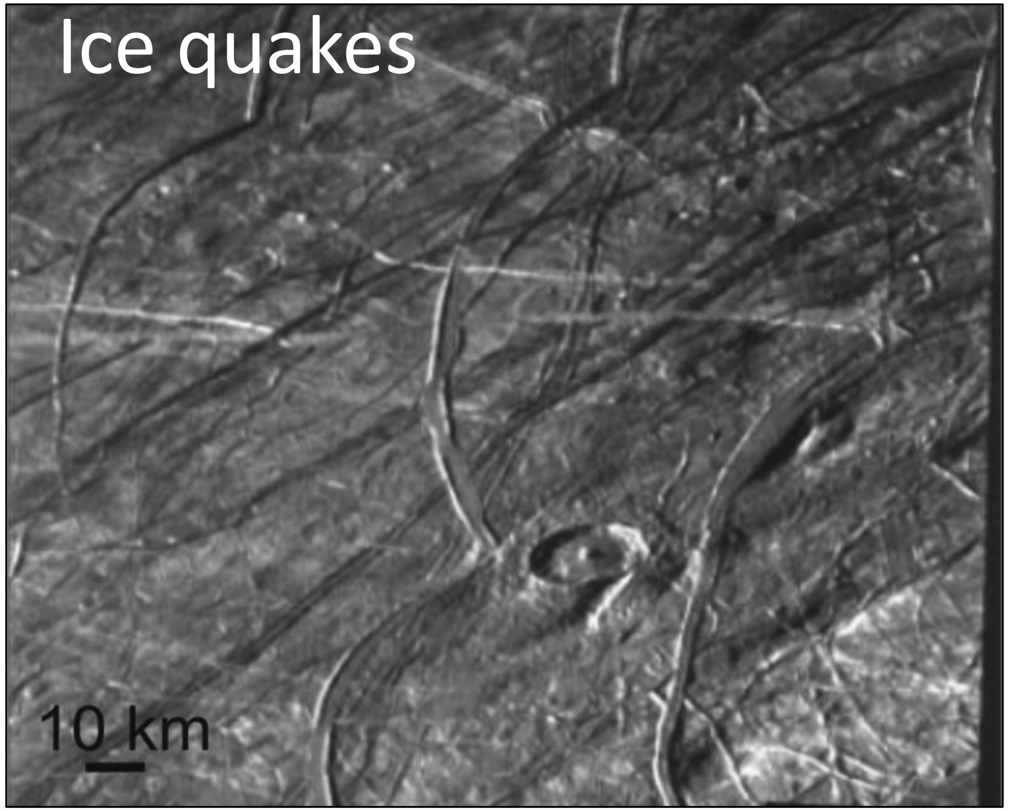


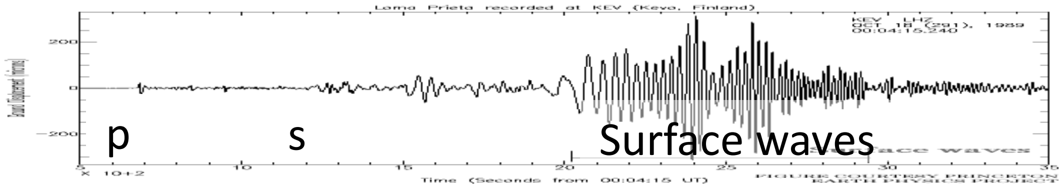
Choblet + 2017 **Vance** + 2014

	Mean Radius in km	Bulk Density in kg m^{-3}	Moment of Inertia (C/MR^2)	Inferred H_2O thickness in km	Rotation Period In hrs	Radiogenic Heat in GW	Tidal Dissipation in GW	Seismic Energy Release in GW (%)
Earth[a]	6371	5514	0.3307	3.5	24	31,000	2636±16	22 (0.8)
Moon[a,b]	1738	3340	0.3929 ± 0.0009	n/a	672	420	1.36±0.19	$6x10^{-7}$ ($0.4x10^{-5}$)
Mars[c]	3397	3933	0.3662 ± 0.0017	n/a	24.6230	3,300	--	?
Europa[d,e,f]	1565.0±8.0	2989±46	0.346 ± 0.005	80-170	84.4	200	>1000 (ice) >1000 (ocean) 1-10 (rock)	?
Ganymede[e,f,g]	2631.17±1.7	1942.0±4.8	0.3115±0.0028	750-900	171.7	500	10^3-10^4 (ice) >1 (ocean)	?
Callisto [e,f]	2410.3±1.5	1834.4±3.4	0.3549±0.0042	350-450	400.5	400	>1 (ice) >4 (ocean)	?
Titan [e,h,i]	2574.73 ±0.09	1879.8±0.2	0.3438±0.0005	500-700	382.7	400	>60 (ice) >11 (ocean)	?
Enceladus [e,h,j]	252.1±0.1	1609±5	0.335	60-80	32.9	0.3	>20 >10 (ocean)	?

a) Williams et al., 2001 b) Goins et al., 1981; Williams et al., 1996; Siegler and Smekrar, 2014 c) Folkner et al., 1997, Nimmo and Faul, 2013 d) Tobie et al. 2003, Hussmann et al., 2006; Vance et al., 2007 e) Chen et al., 2014; Tyler, 2014 f) Schubert et al. 2004 g) Bland et al., 2015 h)

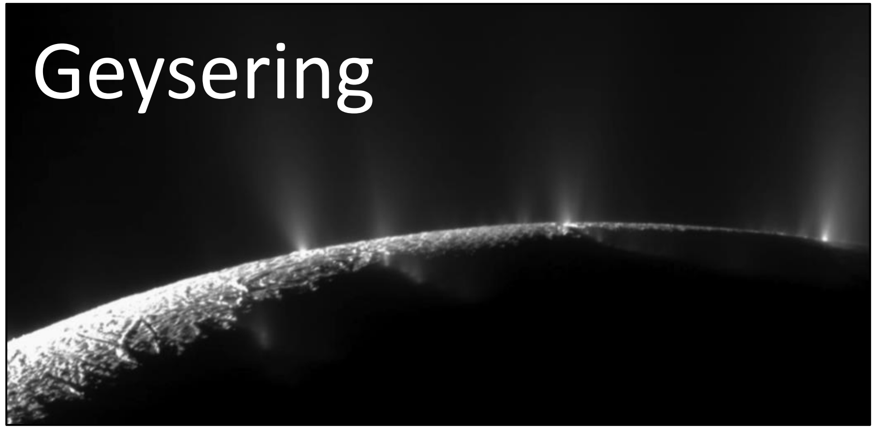
How might an ocean world sound?

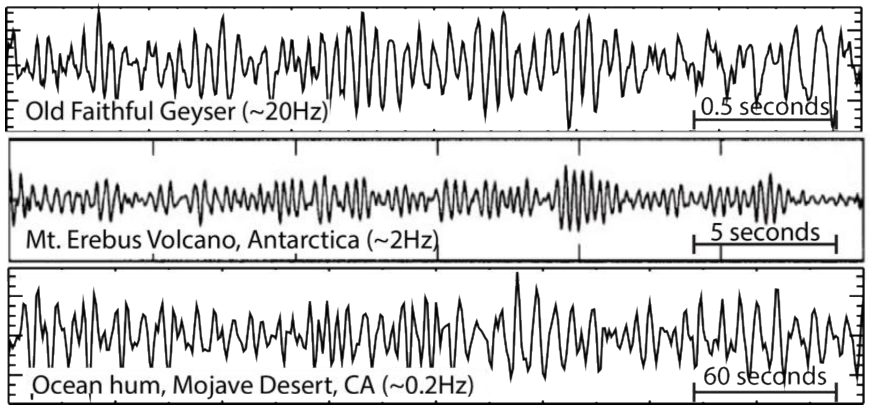


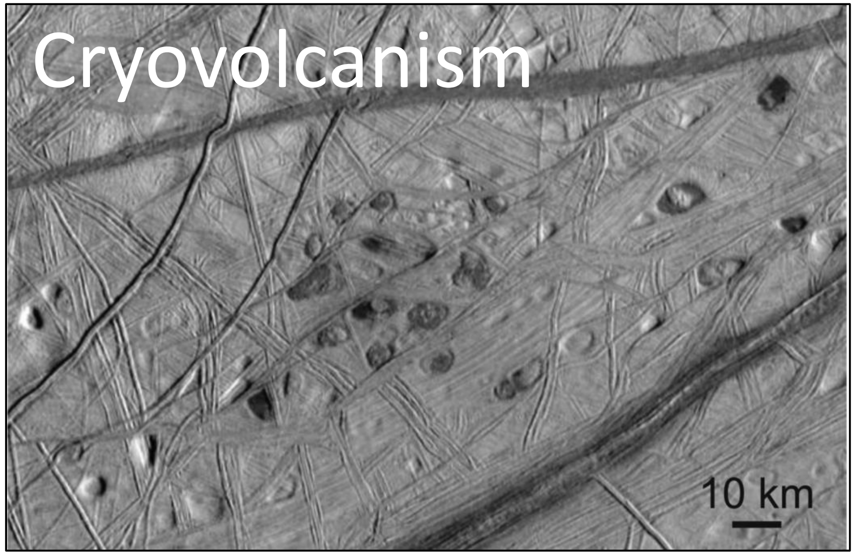


Europa's ice is young and geologically active

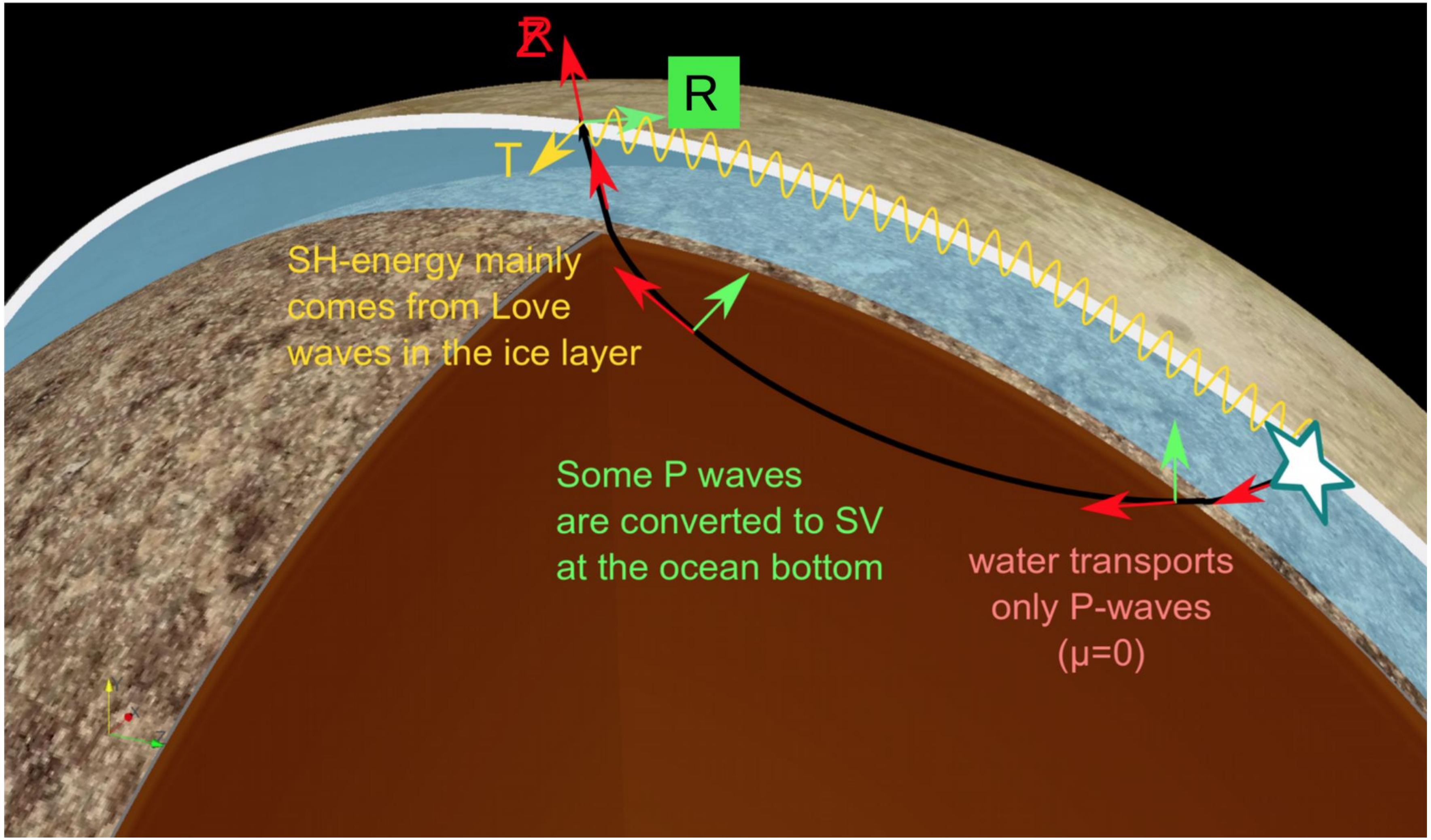
Fluid flow induced seismicity: continuous background "hum"



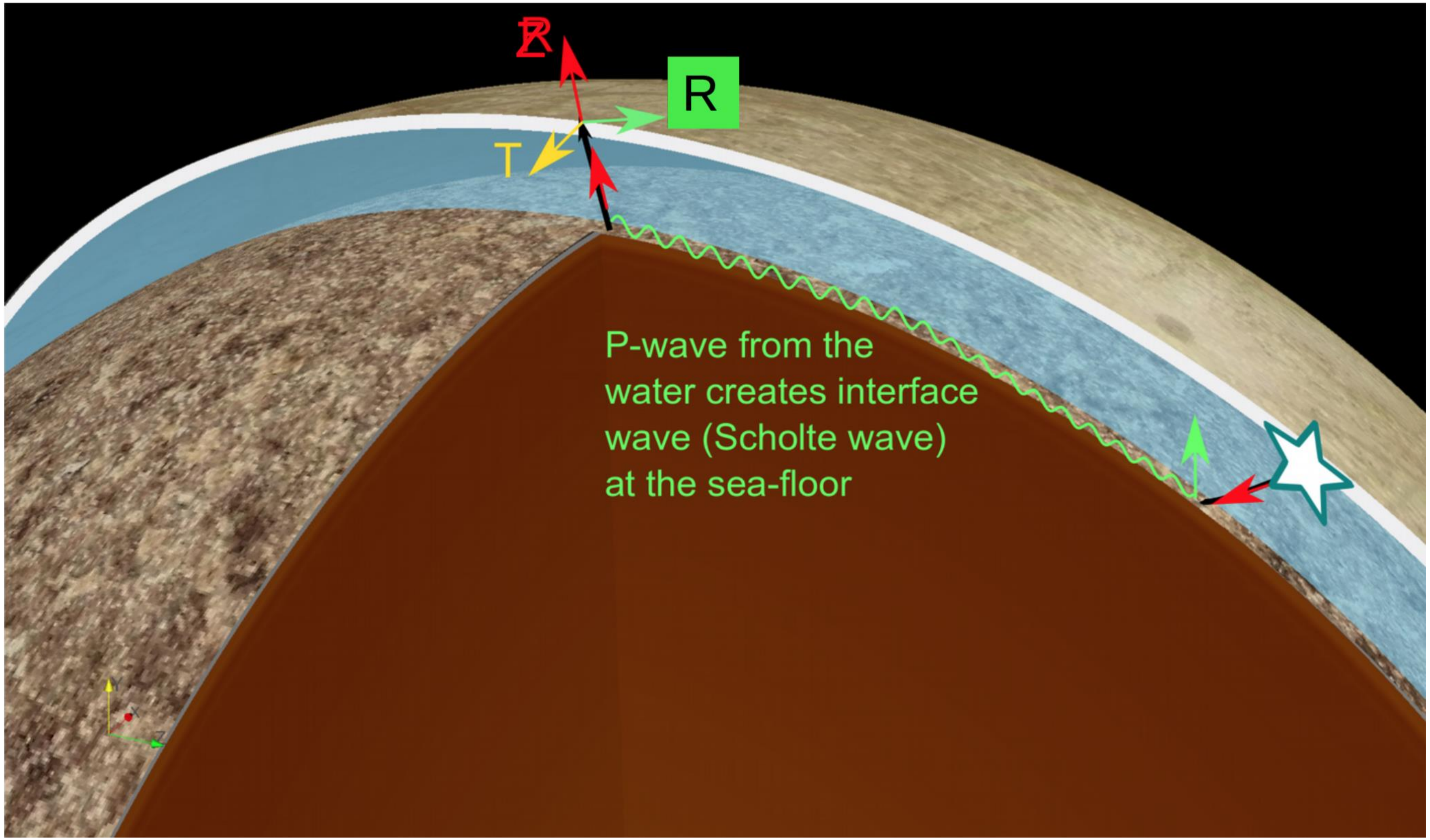




Sensing the mantle and ice

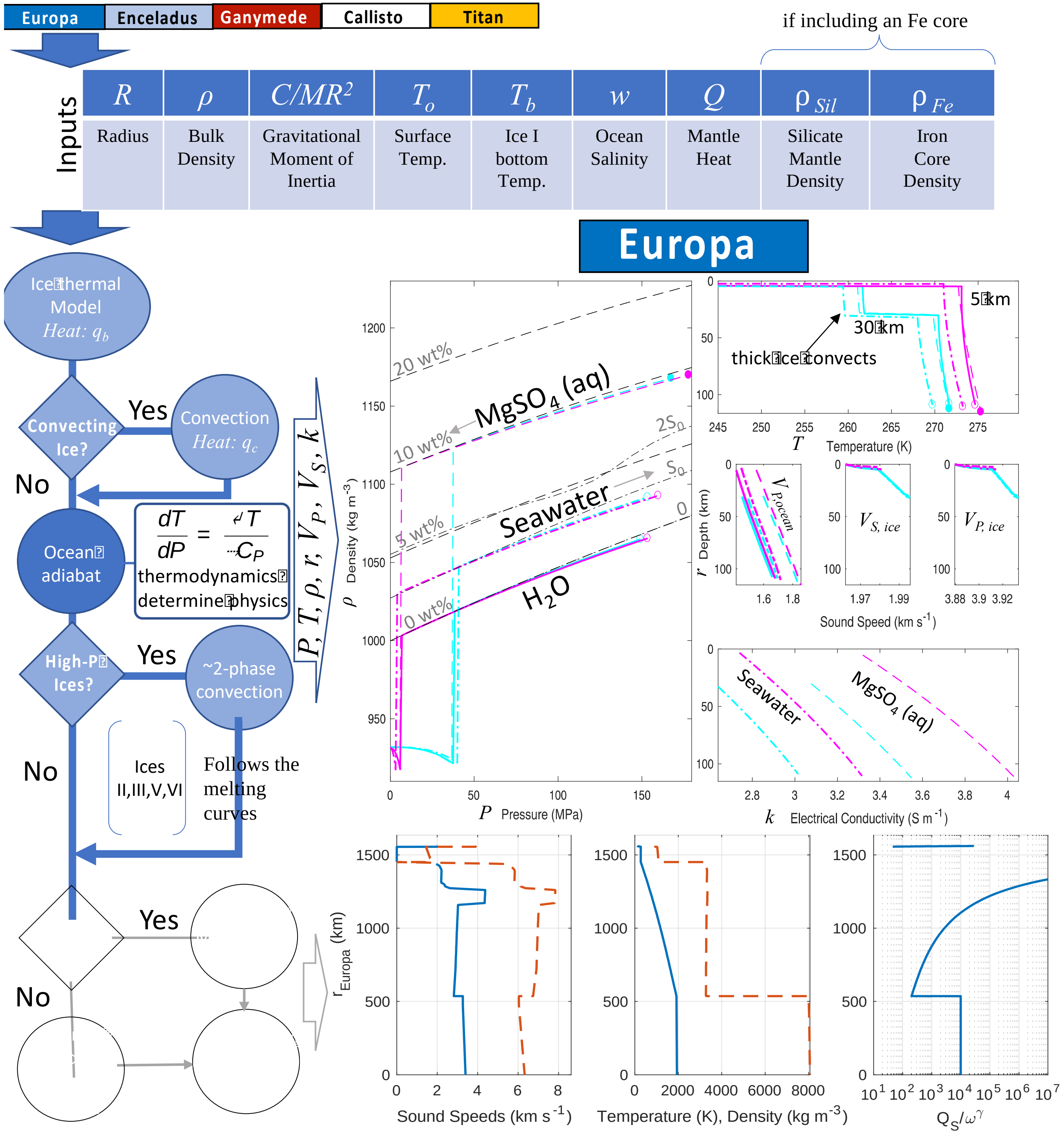


Sensing the mantle and ice



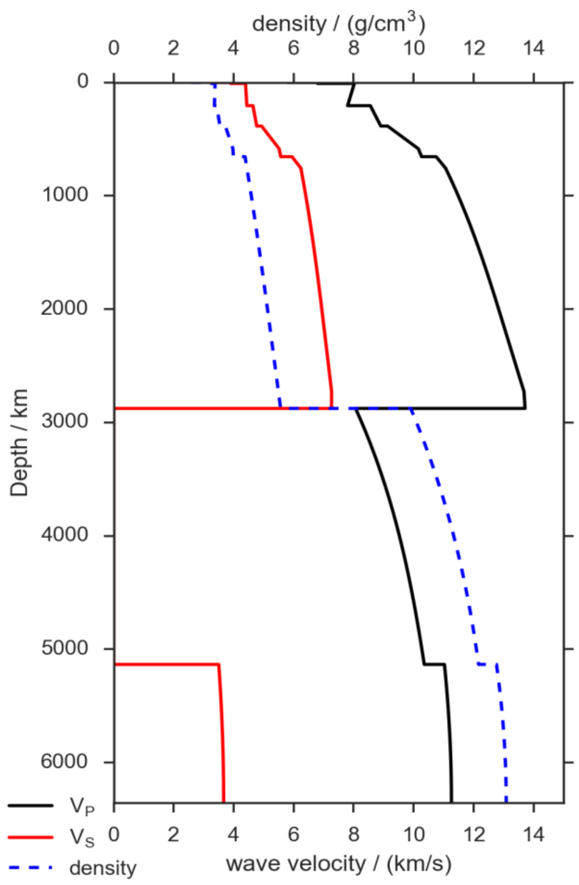
PlanetProfile

github.com/vancesteven/PlanetProfile

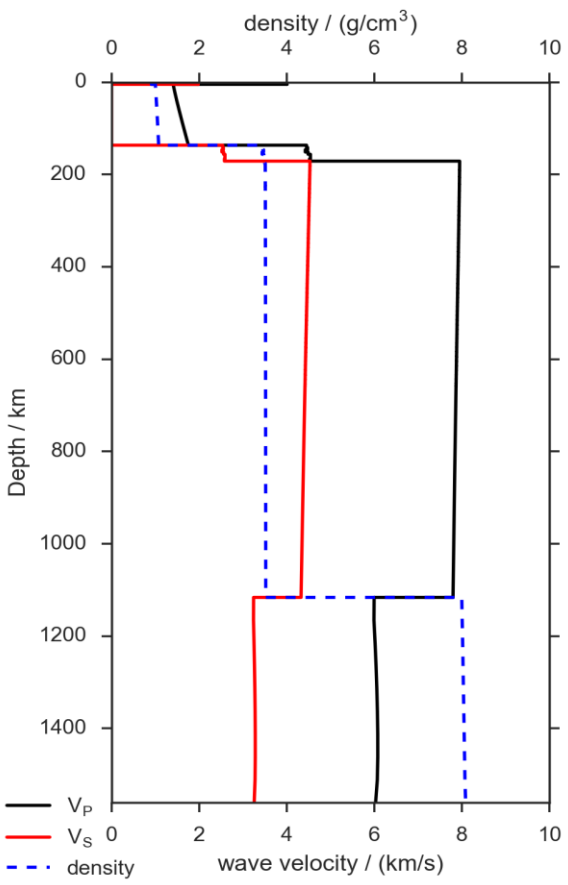


Seismic Models

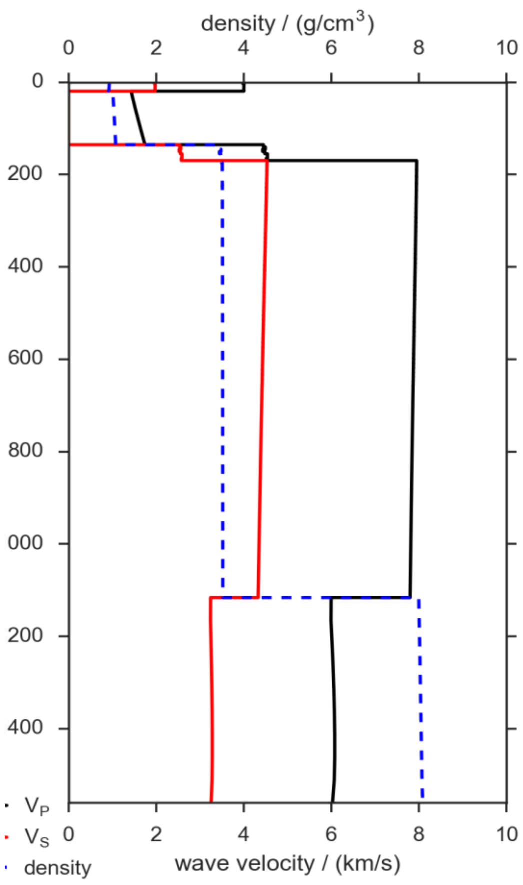
Earth



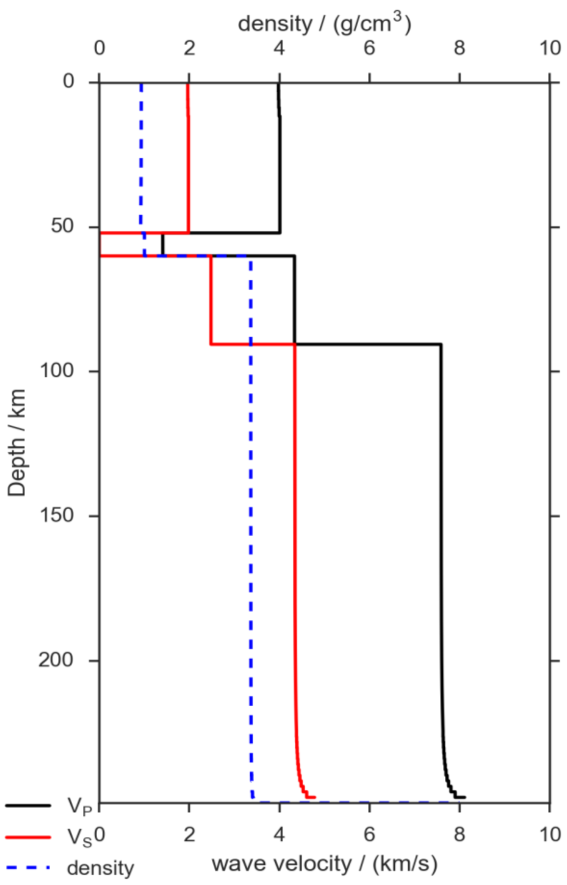
Europa (5km Ice)



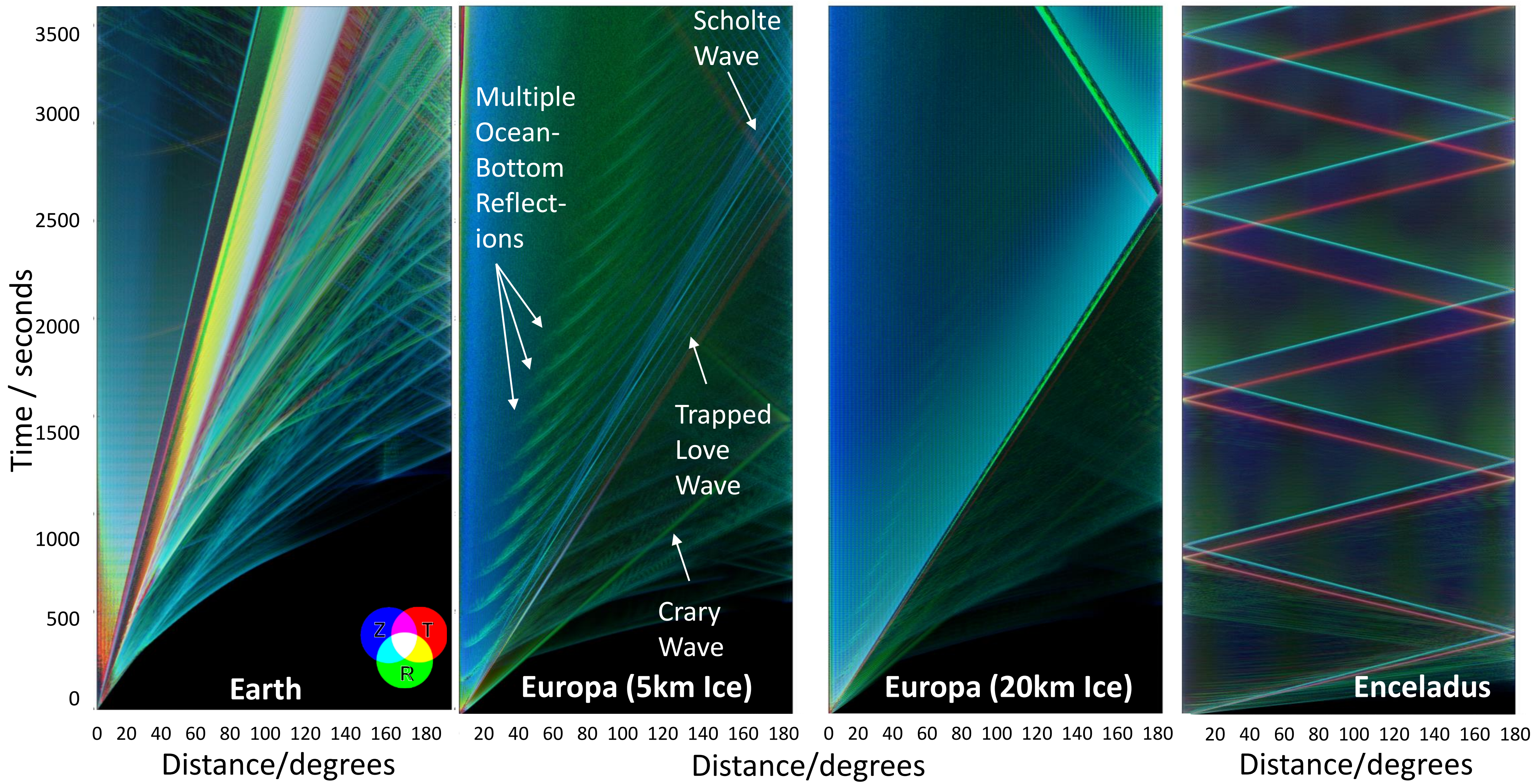
Europa (20km Ice)



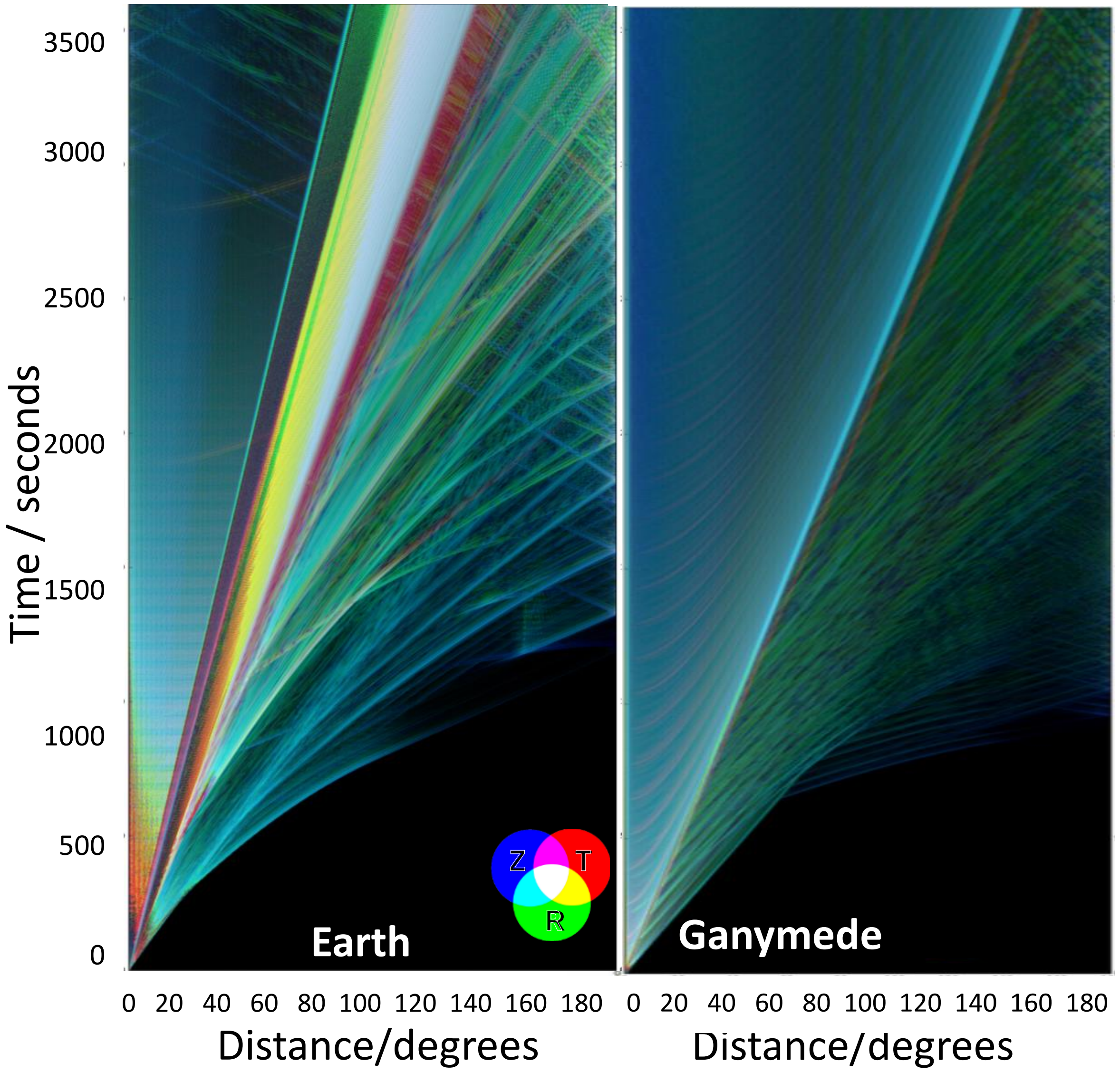
Enceladus

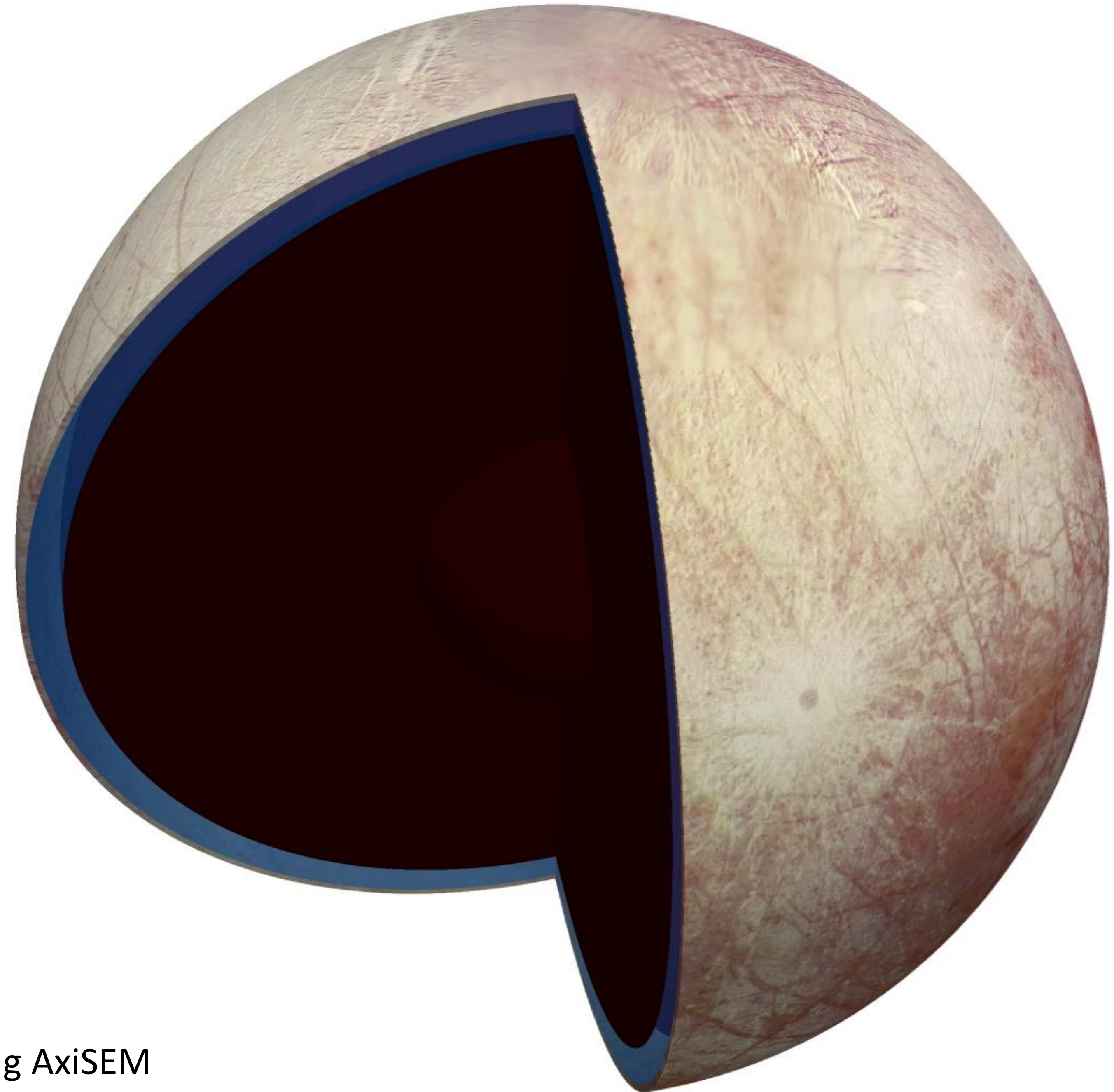


Each Ocean World Has Unique Seismic Signature



Each Ocean World Has a Unique Seismic Signature



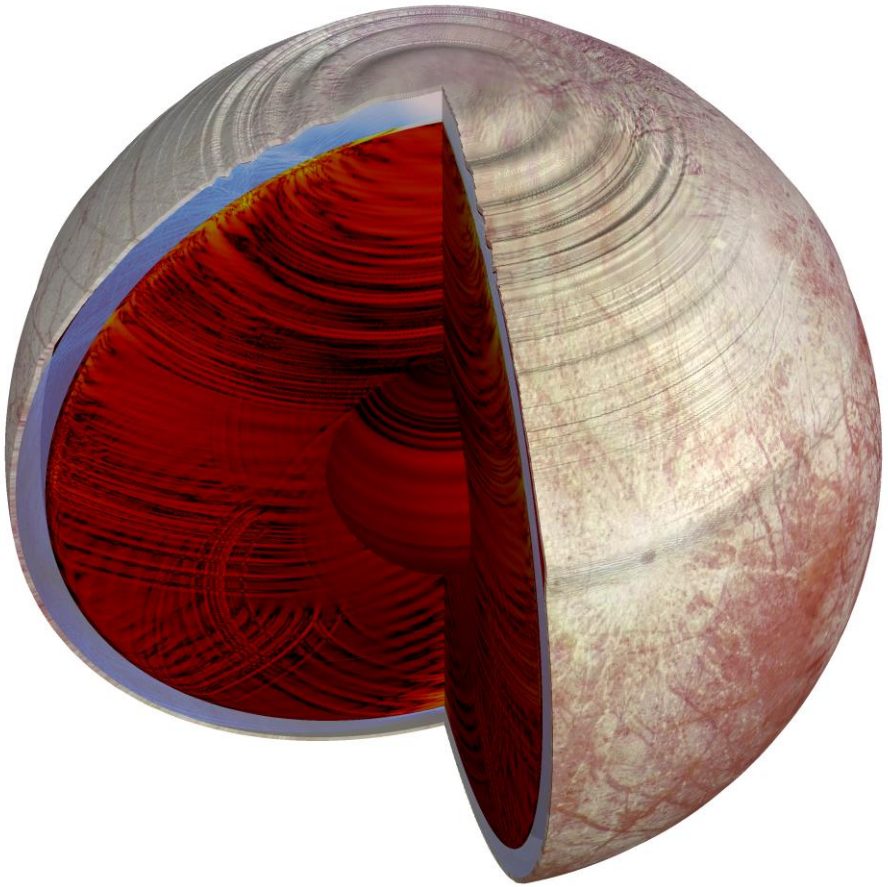


Produced by Simon Stähler using AxiSEM

Estimating the Background Noise

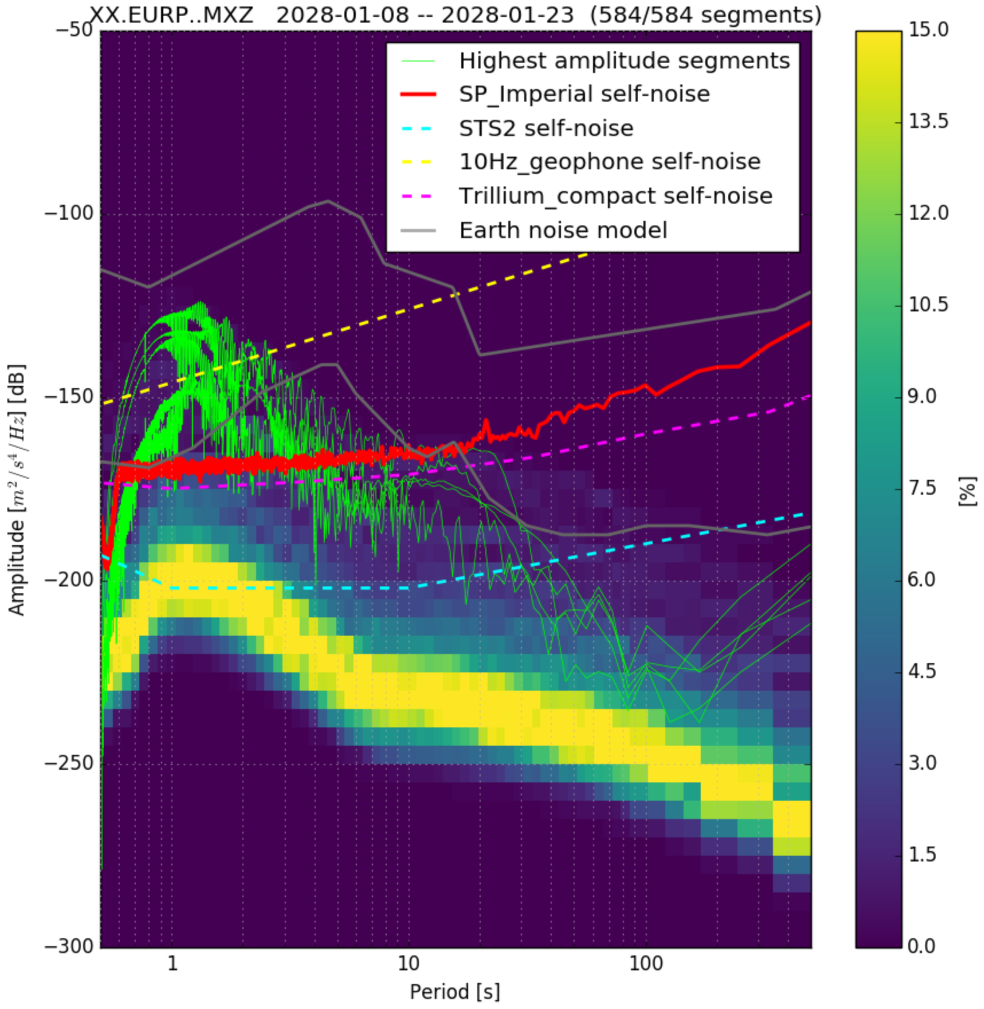
Panning et al., *submitted*

AxiSEM/Instaseis is used to compute a series of 1 week long noise records (figure 3), which are used to compute probabilistic power spectral density plots for different seismicity models and Europa structure models,



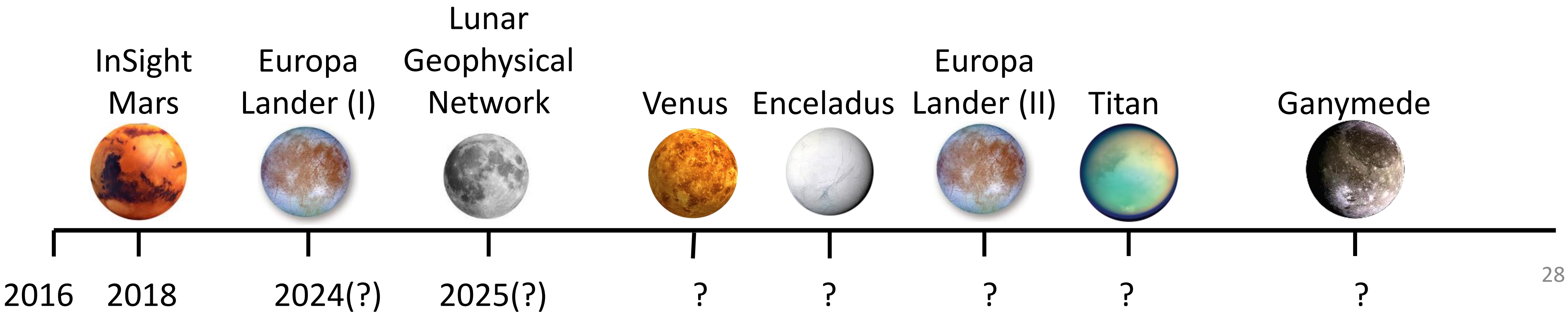
Assumptions:

- Tidal dissipation
- Largest moment release



Conclusions

- Icy ocean worlds are likely to be seismically active
- Seismic activity is likely to be varied, combining ice-quakes, tidal deformation, fluid induced seismicity (geysering, cryovolcanism, ocean circulation & acoustics)
- Each icy world has a unique seismic signature that can constrain habitability
- "Vital Signs" – the unique signs of present day fluid motion may carry fundamental information about the depth and nature of volatiles + ocean circulation
- Future seismometers to ocean worlds must fit within tight power, mass and volume allotments of future landers, but be sensitive enough to maximize science return during exceptionally short missions



Overview of Seismic Sensing Technologies




Earth	Streckeisen STS-2	Trillium Compact	Geophone	MEMS Accelerometer*
Planetary	InSight VBB	InSight SP	Apollo Active Experiment	?*

* Technology has not yet reached sensitivity requirements of Earth & planetary science

- Very Broad Band (VBB)
- High Dynamic Range
- Ultra sensitive
- $$$$

1.4kg

- Broad Band
- High Dynamic Range
- Sensitive
- $$

~0.1Kg
~3cm

- Narrow Band
- Limited dynamic range
- Strong motions
- $

~0.01Kg
~1cm

- Broad Band
- High dynamic range
- Sensitive
- $

Backup

Planetary Seismology???

Prior Seismic Experiments

Table 1 Summary and history of planetary seismology experiments

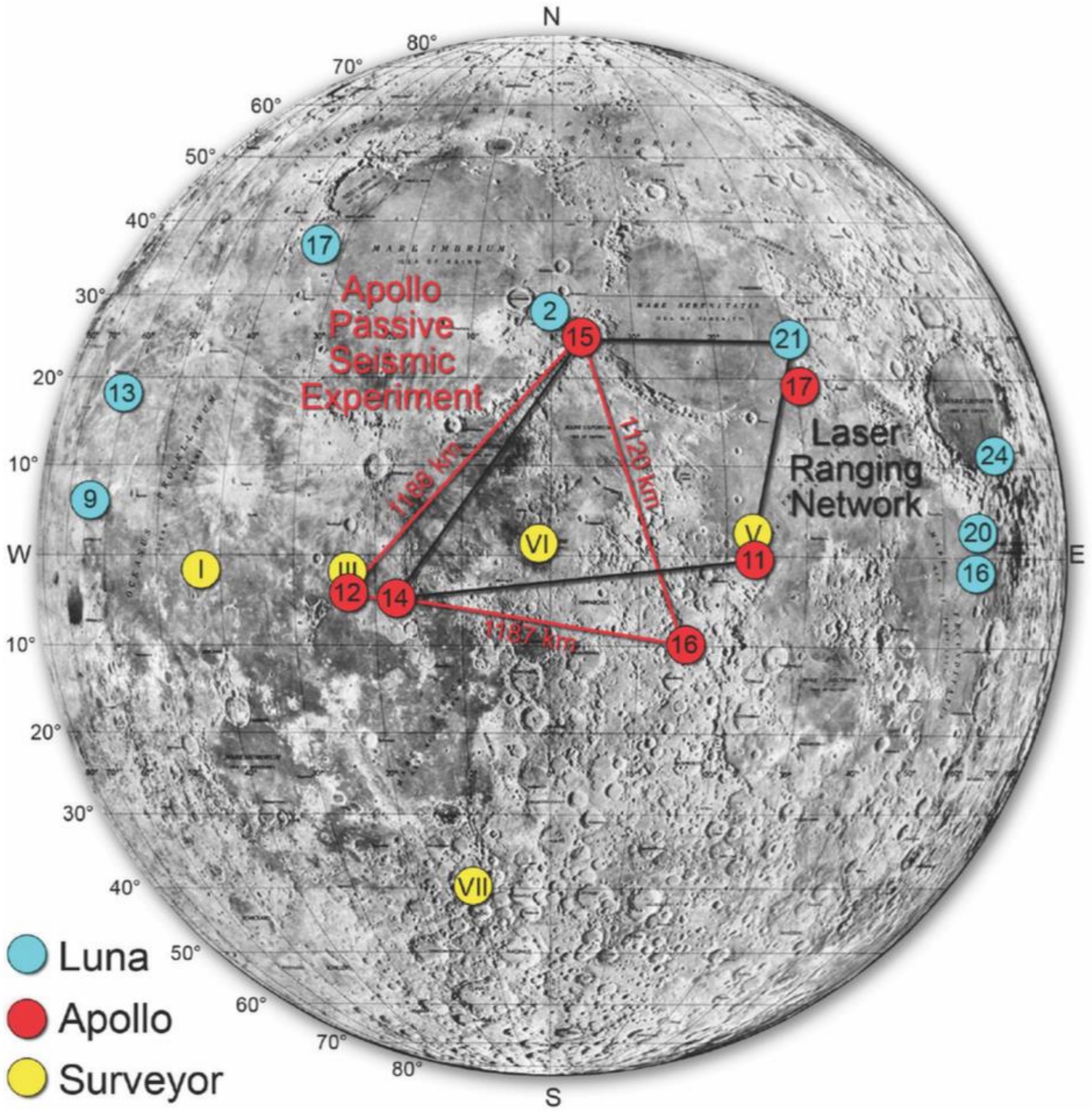
Mission	Launch	Major mission events	Instrument description	Seismometer deployment	Reference
Ranger 3	1962-01-26	Failure due to the booster. Moon missed	Vertical axis seismometer, with a free frequency of 1 Hz. (Mass: 3.36 kg)	Seismometer in a lunar capsule designed for a 130–160 km h^{-1} landing. Batteries powered for 30 days of operations	Lehner *et al.* (1962)
Ranger 4	1962-04-23	Failure of spacecraft central processor. Moon crash.			
Ranger 5	1962-10-18	Failure in the spacecraft power system. Moon missed.			
Surveyor	1966-1968	The seismometer was finally deselected from the payload of the Surveyor missions	Single short-period vertical axis seismometer (mass: 3.8 kg, power: 0.75 W)	Fixed to the lander.	Sutton and Steinbacher (1967).
Apollo 11	1969-7-16	Successful installation. Powered by solar panel, worked during the first lunation and stopped after 21 days	Passive seismic experiment (PSE). triaxis Long-Period seismometer (LP) and one vertical Short-Period (SP) seismometer, with resonance periods of 15 s and 1 s, respectively. (mass: 11.5 kg, power: 4.3–7.4 W)	Installation performed by crew. Seismometers were manually leveled and oriented with bubble level and sun compass. A sun protection/thermal shroud was covering the instruments. Power was delivered by a Plutonium thermal generator for A12-14-15-16	Latham *et al.* (1969, 1970a, 1970b)
Apollo 12 **Apollo 14** **Apollo 15** **Apollo 16**	1969-11-14 1971-01-31 1971-07-26 1972-04-16	Successful installation of a network of 4 stations. For all but the Apollo 12 SP seismometer and Apollo 14 vertical LP seismometer operated until the end of Sep 1977, when all were turned off after command from the Earth. 26.18 active station years of data collected.			
Apollo 13	1970-4-11	Moon landing aborted. No installation of the PSE experiment but lunar crash of the Apollo 13 Saturn-IV upper stage recorded by the A12 PSE.			
Apollo 14 **Apollo 16** **Apollo 17**	1971-01-31 1972-04-16 1972-12-07	Successful installation and operation of the active seismic experiments. Seismic sources were thumper devices containing 21 small explosive sources and a rocket grenade launcher with four sources exploding up to 1500 m on A-14 and A-16. Eight sources were used containing up to 2722 *g* of explosive and deployed at 3500 m by astronauts	String of three geophones on A-14 and A16 and on four geophones on A-17. Frequency was 3–250 Hz.	Geophones were anchored into the surface by short spikes as they were unreeled from the thumper/ geophone assembly.	Watkins and Kovach (1972) Kovach and Watkins (1973a)

(*Continued*)

Table 1 (Continued)

Mission	Launch	Major mission events	Instrument description	Seismometer deployment	Reference
Apollo 17	1972-12-07	Deployment of the Lunar Surface Gravimeter. The gravimeter was unable to operate properly due to an error in the design of the proof mass.	Gravimeter designed for gravity waves detection. Additional long-period vertical seismic output (10^{-11} lunar *g* resolution) for free oscillation detection, with a 16 Hz sampling.	Installation performed by crew.	Weber (1971)
Viking Lander 1	1975-08-20	Successful landing but instrument failure.	Short-period instrument, with an undamped natural period of 0.25 s, a mass of 2.2 kg, a size of 12 × 15 × 12 cm and a nominal power consumption of 3.5 W.	The seismometer was installed on the Lander platform. No recentering was necessary since the three-axis seismometer had been designed to function even when tilted to up to 23°	Anderson *et al.* (1977a, 1977b)
Viking Lander 2	1975-09-09	Successful landing and 19 months of nearly continuous operation. Too high wind sensitivity associated to the elastic recovery of the *Viking* landing legs to the loading of the station by pressure fluctuations induced by the wind.			
Phobos 1-2	1988-07-07 1988-07-12	Respectively: Lost during transfer to Mars and Phobos; contact lost just before the final phase of lander deployment, after Mars orbit insertion		Instrument onboard the long-service lander.	Surkov (1990)
Mars 96-Small surface stations	1996-11-16	Failure of the Block-D propulsion system in parking orbit. Earth re-entry. Two small stations and two penetrators lost.	Long-period vertical axis seismometer (0.1–4 Hz, 0.405 kg for the sensor) combined to a magnetometer. 55 mW of power	Seismometer in the small surface station. Semi-hard landing (200*g*–20 ms). Nominal operations of one Martian year with 90th first days of nearly continuous mode with internal batteries	Lognonné *et al.* (1998a)
Mars 96 Penetrators			High-frequency seismometer (10–100 Hz, 0.3 kg, 20 mW)	Seismometer in the penetrator. Hard landing. Nominal operations of one Martian year.	Kravroshkin and Tsyplakov (1996)
Rosetta	2004-03-04	Landing on the comet 67P/Churyumov-Gerasimenko planned a few months after rendezvous, expected on 22-05-2014	CASSE/SESAME experiment: High-frequency accelerometer covering the frequency bandwidth ~10–20 kHz.	Instrument mounted on the lander	(Kochan *et al.* 2000)

Lognonné 2007


N
S
W
E
Apollo
Passive
Seismic
Experiment
Laser
Ranging
Network
1188 km
1120 km
1187 km
Luna
Apollo
Surveyor
17
2
15
21
17
13
24
9
20
16
VI
V
I
III
12
14
11
16
VII
80°
70°
60°
50°
40°
30°
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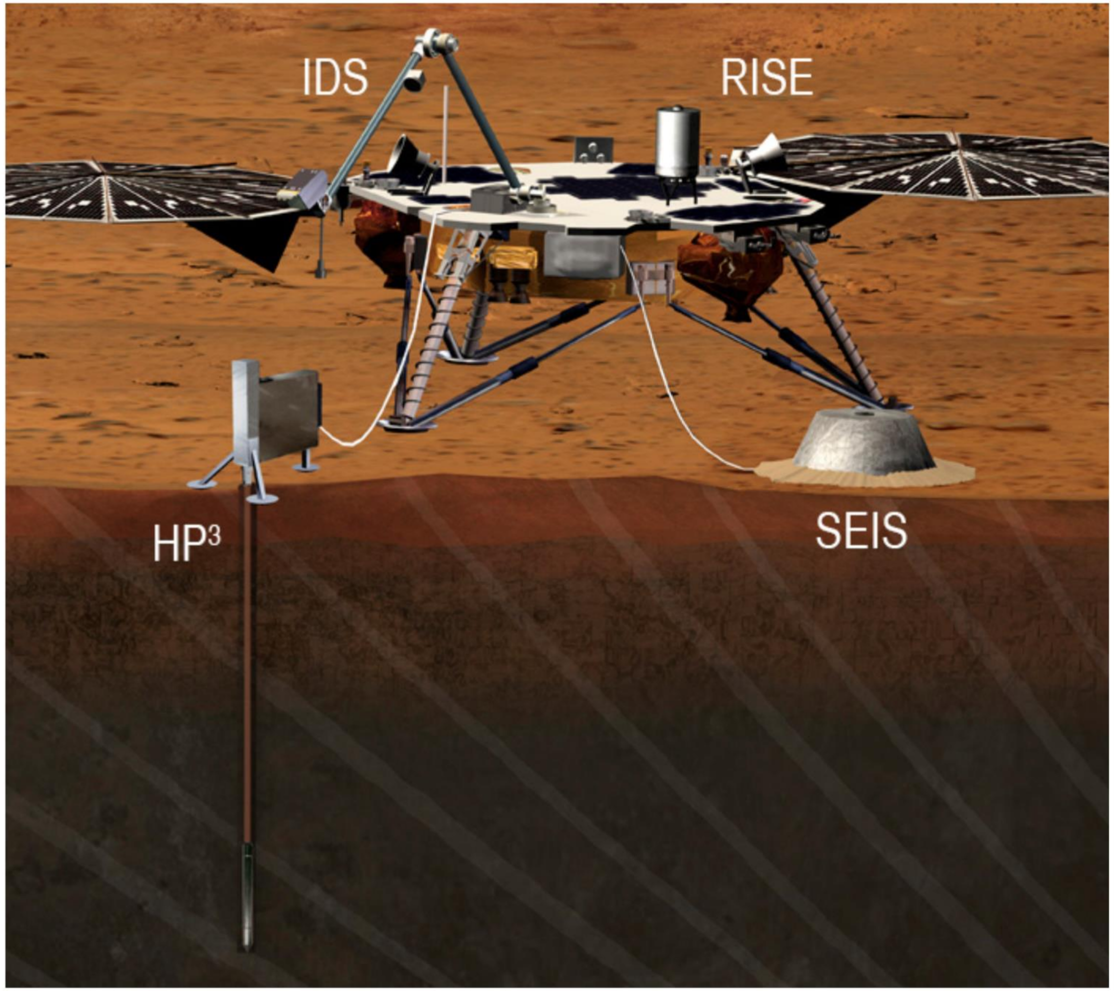
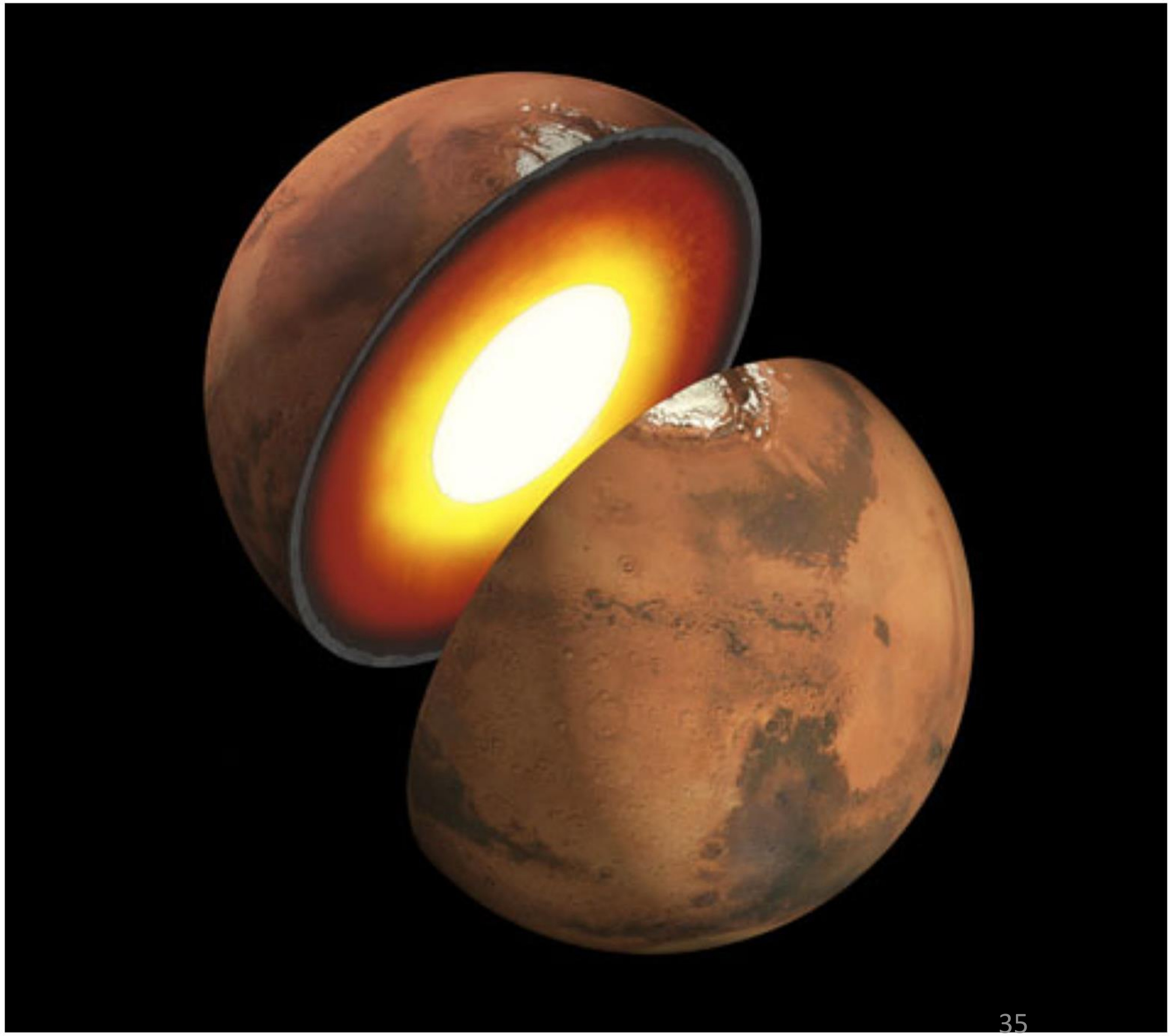
40°
50°
60°
70°
80°


IDS
RISE
HP3
SEIS



	Radius (km)	Density (kg m^{-3})	Moment of Inertia
Europa	1565.0±8.0	2989±46	0.346±0.005
Ganymede	2631±1.7	1942.0±4.8	0.3115±0.0028
Callisto	2410.3±1.5	1834.4±3.4	0.3549±0.0042
Enceladus	252.1±0.2	1609±5	0.335
Titan	2574.73±0.09	1879.8±0.004	0.3438±0.0005

Fluid Properties

- $MgSO_4$ (aq) – Vance and Brown 2013, Vance et al. 2014
  - 0-2 molal; 250-400 K; 0-2 GPa
- Seawater (NaCl) — Gibbs Seawater (McDougall 2011)
  - 0-2S0; 250-400 K; 0-0.1 GPa
- NH3 (aq)
  - 0-10 wt%; 250-400 K; 0-2 GPa

Sound speed in ice

from fits to measurements around -35°C

Crystalline Phase	K_S GPa	K'_S	K''_S GPa^{-1}	μ GPa	μ'	μ'' GPa^{-1}
I_h	9.5	0.33	-0.026	3.3	0.537	-.025
II	13.89	1.6	—	5.15	3.5	—
III	8.9	3.65	—	2.7	6.55	—
V	11.8	4.8	—	5.7	0.9	—
VI	14.6	4.1	—	5.0	3.0	—

based on Shaw 1986 and Gagnon et al. 1988, 1990

$$V_S = \left[\frac{\mu}{\rho}\right]^{1/2}$$

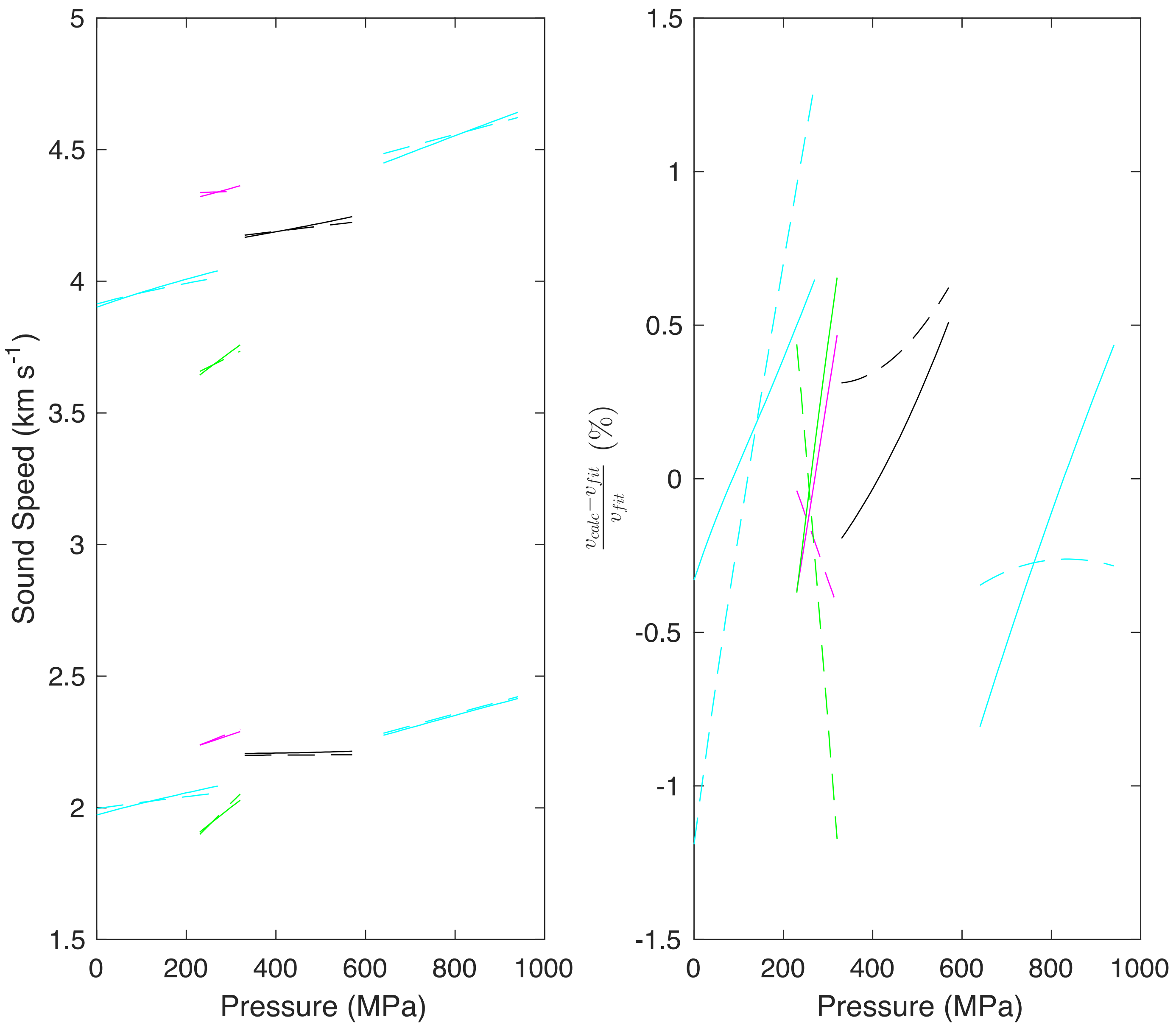
$$V_P = \left[\frac{K_S}{\rho} + \frac{4}{3}V_S^2\right]^{1/2}$$

forward model for bulk sound speed from ice equations of state based on density and phase boundaries

$$\frac{\partial \rho}{\partial P}_T = \frac{1}{v_c^2} + \frac{\alpha^2 T}{C_P}$$

Choukroun et al. 2010

Vance et al., in prep.


5
4.5
4
3.5
3
2.5
2
1.5
0
200
400
600
800
1000
Sound Speed (km s^{-1})
Pressure (MPa)
1.5
1
0.5
0
-0.5
-1
-1.5
$\frac{v_{calc}-v_{fit}}{v_{fit}}$ (%)
Pressure (MPa)

Instrument Performance Implication for Science Return